Collapse, Erosion, Condition, and Restoration 12

12.1 Collapse

Man-induced ecosystem degradation in Iceland has had more dramatic consequences than in most other countries of the northern hemisphere (Fig. 12.1). Poorly vegetated land now covers >40 % of the country, with the remaining ecosystems in a much poorer state compared to optimal conditions (e.g., Thorsteinsson et al. 1971; Arnalds 1987, 1988; Arnalds and Aradottir 2011). Woodlands were reduced from about 25 % to almost total elimination about 100 years ago (Sigurdsson 1977; Hallsdottir 1995; Aradottir and Arnalds 2001; Aradottir and Eysteinsson 2005). A large proportion of the Icelandic wetlands were drained during the last century (Gardarsson et al. 2006). The Icelandic ecosystem collapse is often cited with other examples of disastrous human impacts, such as in Jared Diamond's book *Collapse* (2005), Montgomery's book *Dirt* (2007), and the Icelandic example is given considerable attention in *Desertification, Land Degradation, and Sustainability* by Imeson (2012). Recent Icelandic natural history is not only about destruction and collapse; it is also about survival of man. Streeter et al. (2012) stated that "Iceland occupies a position of precarious survival, defined by not becoming extinct, like Norse Greenland, but having endured, sometimes by the narrowest of margins." A comprehensive overview of the nearly 1,140 years of human history of Iceland, emphasizing its location as a marginal environmental area, was published by Karlsson (2000).

Degradation of ecosystems on Earth is a severe threat to soil resources and is therefore one of the most important aspects of soil science and ecology. Large-scale land degradation is addressed in other World Soil Book Series books published by Springer, such as in *The Soils of Chile* (Casanova et al. 2013) and *The Soils of Mexico* (Krasilnikov et al. 2013), but in addition to similarities reflected by severe degradation, these countries have a large share of volcanic soils as are found in Iceland.

There is a considerable wealth of research to give insight into the collapse of Icelandic ecosystems, which will be discussed below with references to aid those with interest in the subject. The current state of the resources, including vegetation distribution, major vegetation classes, and erosion activity is relatively well documented. Research methods and the state of the land will be described in this chapter. Finally, restoration activities in Iceland will be discussed briefly.

12.2 Resilience and Impacts: A Little History of Soils and Vegetation

12.2.1 Evidence of Ecosystem Changes

Iceland was almost entirely covered by glacier during the Pleistocene glaciation. After the retreat of the glacier, some 9,000–10,000 years ago, Iceland gradually became nearly fully vegetated, with plants species surviving the glaciation or brought to the island by wind, birds, or other means. The climate has fluctuated considerably during the Holocene, causing large-scale vegetation changes, especially in abundance of wetland species and birch woodlands. Einarsson (1968) splits the Holocene vegetation history in Iceland into periods or zones based on pollen analysis, with alternating birch and mire/wetland periods, reflecting climatic fluctuations during the period. The current epoch is the second mire period, but birch was dominant with apparent dryer conditions during two prehistoric periods (see also Hallsdottir 1995; Hallsdottir and Caseldine 2005). But the most dramatic change during the Holocene in vegetation composition and soil cover occurred with the arrival of man to Iceland.

Considerable knowledge has been gathered from multiple sources about the past riches and environmental changes in Iceland, but these sources were summarized by Arnalds (1987). These include: (i) medieval written records such as the Sagas and Annals; (ii) vegetation and soil remnants in severely degraded areas; (iii) pollen analyses; (iv) old charcoal pits and remnants in present day deserts (Fig. 12.2); (v) aeolian deposition rates; (vi) old place names; (vii) studies of lake sediments; (viii) archeological research;

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Fig. 12.1 Visitors in an Icelandic desert. Small soil and vegetation remnants to the *right* of the men. This area was previously fully covered with >1 m thick Andosol and birch forest, which was used as a source for fuel wood. The surface is now 1–2 m lower than it was prior to the destruction and vegetation is scarce. *Photo* © G.K. Johannesson

Fig. 12.2 Charcoal pits in present day deserts. A stone ring marks the place where the charcoals were found. Vegetation and soil remnants in the background. In many areas, remnants of charcoal making from cutting down birch trees are found where there is presently a desert. Most such areas can potentially be restored to former grandeur. *Photo* Andres Arnalds, ISCS

(ix) vegetation of naturally protected areas such as on islands in large rivers. There is a famous passage in *The Book of Icelanders* written by Ari Fróði (Ari the Wise) few centuries after the Settlement, which states that Iceland was covered with woodlands from the shore to the mountains at the time of the settlement. Although the validity of this statement can be questioned, Icelanders have always been aware of vast environmental changes that have occurred since the island was settled.

Many noted the poor state of the land early on, including the geographer Th. Thoroddsen and Saemundur Eyjolfsson during the nineteenth century (see Sigurjónsson 1958; Arnalds 1988). It became increasingly evident that heavy grazing the year around by sheep and wood harvesting for fuel caused widespread damage, which prompted the writing of many papers, including a landmark paper by Bjarnason (1942) on the results of overgrazing and wood cutting.

The Sagas and other written medieval documents provide many clues for the state of the land. Old place names indicate the presence of farms and forested areas where now there is severely degraded land. The meaning of some terms have changed, such as the common term "holt" which previously meant forested hill but now an unsheltered or barren area.

Erosion history has been studied in several areas in Iceland. Gudbergsson (1975) studied erosion history of the Skagafjörður district, North Iceland, mostly based on aeolian sedimentation rates, historical records, and thin sections of soils. He also published an extended review of the vegetation and land use history of NW Iceland (Gudbergsson 1996). Sveinbjarnardottir et al. (1982) and Gerrard (1985) studied erosion and landscape stability in southern Iceland. Gisladottir (1998), Gisladottir et al. (2010) have made detailed studies of the erosion history of the Krísuvík area (Coastal Southwest) and in West Iceland (Gisladottir et al. 2011). Sigbjarnarson (1969), Gisladottir et al. (2005) and more recently Greipsson (2012) studied the degradation and soil erosion south of Langjökull Glacier, where the combination of grazing, wood cutting, climate change (cold spells), and changes at the glacial margins acted to cause severe ecosystem destruction. Glacial margins, glacial rivers, and lakes with unstable water levels act as sand sources for the advancement of advancing sand fronts, with sustained sand drift enhanced by dry katabatic winds from the Langjökull glacier. All these studies provide valuable insight into the history of degradation in Iceland.

12.2.2 Aeolian Deposition Rates

Aeolian deposition rates are commonly used in Iceland to infer environmental changes, with rapid rates signaling erosion periods, but slow rates indicate periods of less aeolian activity, hence: little or less geomorphic activity associated with land degradation. The rates can be determined by measuring depths between tephra layers of known age. Sigurdur Thorarinsson pioneered the scientific field of tephrochronology and published a comprehensive review in 1961 showing that the aeolian sedimentation rates increased dramatically after the Settlement, as a result of wind erosion of soils. His aeolian deposition rate studies were followed by Sigbjarnarson (1969), who studied land degradation south of the Langjökull Glacier, Gudbergsson (1975) in North Iceland and the method was employed in a number of studies by Andrew Dugmore and coworkers (e.g., Dugmore et al. 2000). Micromorphological studies show that a large proportion of the aeolian deposits dated after the Settlement consist of redistributed soils. This is exemplified by the occurrence of redistributed rhyolitic tephra grains easily identified under the microscope and often under a hand lens (e.g., Gudbergsson 1975; Arnalds 1990; Stoops et al. 2008). The redistributed soil materials are mixed with other aeolian materials that originate from the major dust source areas discussed in Chap. 11. It was shown in Chap. 8 how organic carbon levels dropped in soils with high rate of aeolian deposition during the major advent of soil erosion during the Middle Ages.

Aeolian deposition rates remain an important part of the methodology to study past environments (e.g., Gisladottir et al. 2010; Streeter and Dugmore 2012). Care, however, must be exercised in interpreting aeolian deposition data. It is appropriate in this text about soils and the Icelandic soil environment to raise some points of caution in relation to aeolian deposition rates.

(i) Recent studies show that the most active present day sources of aeolian materials are "confined" areas of high dust productivity (Arnalds 2010; Dagsson-Waldhauserova et al. 2013; Arnalds et al. 2014). In some areas, much of the most erodible Andosols were depleted during early periods of erosion activity during the Middle Ages, leaving deserts behind. Aeolian activity would subsequently decrease from such areas, while the dust sediment production from the present day main dust sources is likely to have increased during the twentieth and twenty first centuries with glacial retreat (see Fig. 12.3).

(ii) Chemical weathering occurs after the aeolian materials are deposited with some materials being lost (mobile elements). Clay minerals are formed and organic matter added to the soils, with subsequent changes in bulk density. Losses by chemical weathering are not accounted for, nor are the organic matter contents and changes and differences in bulk density (see Arnalds 2010). These methods use bulk thicknesses to calculate rates in mm $year^{-1}$. Considering these factors and calculating deposition in g m^{-2} accounting for these factors instead of using

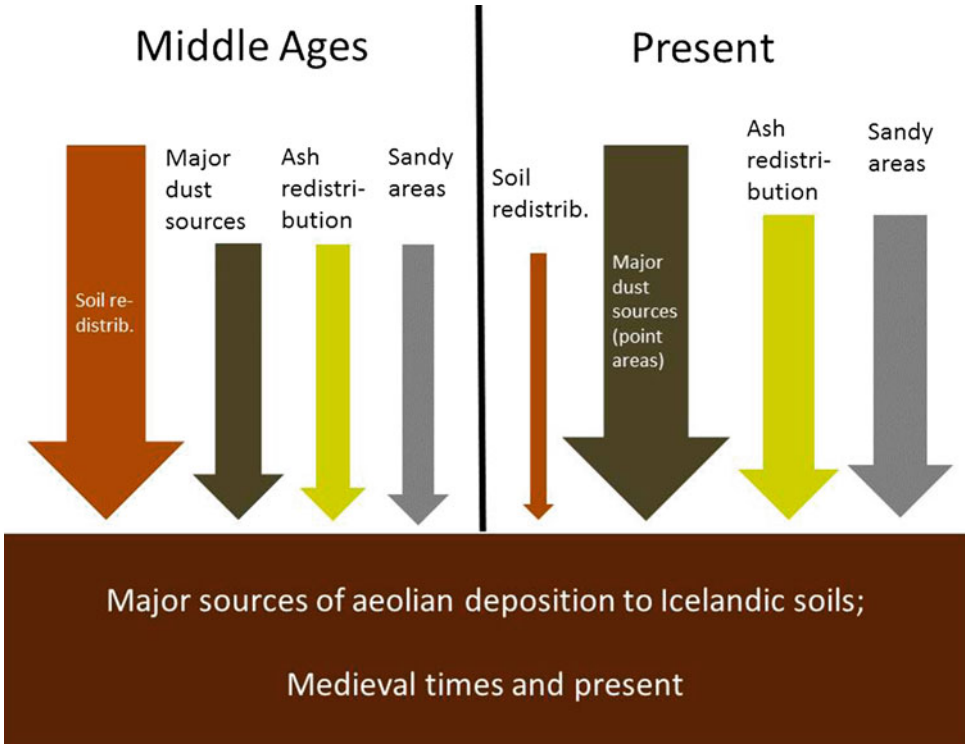

Fig. 12.3 Schematic drawing indicating a shift in contribution from the major dust sources from the Middle Ages to the present. Soil redistribution is presently not as large component compared to earlier erosion periods while major glaciofluvial sources are more active now, together with growing sandy deserts and redistributed ash from the poorly vegetated areas after volcanic eruptions

thickening rates in millimeter, would possibly yield somewhat different results.

Chemical weathering is minimal in areas of high rates, but can be considerable where the rates are low (see Oskarsson et al. 2012 and Chap. 9 on soil genesis). Soil strata found at depths is usually significantly weathered and simply using depth increments between tephra layers would indicate slower accumulation than actual initial rates when these materials were at the surface (materials being lost due to weathering over time). With the weathering, the bulk density of the materials changes from >1.1 to 0.6–0.8 g cm^{-3}, which can lead to underestimation of original aeolian deposition rates.

(iii) Aeolian deposition rates are affected by spikes of aeolian activity after tephra deposition events as exemplified by the 2010 Eyjafjallajökull deposition (Arnalds et al. 2013), but similar large scale spike effects are reported for the 1990 Hudson eruption in Chile (Wilson et al. 2011; Casanova et al. 2013). Volcanic tephra that falls on desert areas, even in small quantities, is unstable, creating such spikes on surrounding vegetation. In Iceland, growing desert areas after the Settlement have possibly amplified aeolian spikes with time.

It should be noted that variable ecosystem surfaces and multiple erosion types make interpretation of aeolian data *per se* not sufficient to understand erosion processes and erosion history at a given site. Wind erosion would not have been the major erosion process in many areas, such as west Iceland with relatively wet soils dominating, and thin dryland soils in between, which are not very susceptible to wind erosion (the area is still relatively well vegetated except for steep hills). Water erosion would be the dominant erosion process, dominating the hillsides. Ideal sites for general interpretations of aeolian records for extensive areas (e.g., highland areas) would be located well within vegetated areas (not at desert margins) relatively far downwind from the degraded areas.

12.2.3 Vegetation—Pollen

Vegetation mapping was started during the middle of the twentieth century, and the results highlighted the poor state of the ecosystems. Vegetation classes in relation to land condition were discussed briefly in Chap. 4, but a system separating land condition classes are introduced later in this chapter. Ingvi Thorsteinsson published a monograph on vegetation protection (*Gróðurvernd*) in 1972 and an overview of the range resources in English (Thorsteinsson et al. 1971). Pollen analyses in Iceland were pioneered by Thorarinsson (1944), Einarsson (1962) and later by Hallsdottir and others (see Hallsdottir and Caseldine 2005), which showed dramatic changes in vegetation composition after the Settlement. Other detailed pollen studies include those of Lawson et al. (2007) from the Lake Mývatn area (NE Iceland) and

Fig. 12.4 Birch trees and vigorous vegetation in the Viðey island (Wooden-Island) in the Þjórsá river in South Iceland. The land in the background is severely degraded, but has been restored to a certain degree. *Photo* © Anna Sigridur Valdimarsdottir

Erlendsson et al. (2009) in southern Iceland, which showed less dramatic vegetation change at the Settlement at the southern coastal location in comparison to many previous studies.

Vegetation studies in areas naturally protected from heavy grazing show vigorous vegetation at such locations, but the studies include those of Jonsdottir (1984) in a protected highland area in North Iceland, and by Valdimarsdottir and Magnusson (2013), who studied an island in the major glacial river of Thjórsá in the South (Fig. 12.4).

12.2.4 Impacts, Resilience and Stability

Volcanic eruptions periodically cause deposition of volcanic tephra (ash). The impact of the tephra is largely determined by the thickness of the tephra that is deposited and vegetation height receiving the deposition (Arnalds 2013). Composition of the vegetation is also important, with mosses and lichens being vulnerable to deposition impacts. Grazing affects vegetation height, composition and nutrient levels in the soil, and long-term heavy grazing reduces both resilience and stability of the systems. The relationship between ecosystem resilience and stability on one hand and the periodic impacts of volcanic events and cold spells on the other has been stressed by many (see Arnalds 2013). The time of dramatic ecosystem changes begins immediately after the Settlement around 870, but exact timing of disturbances varies somewhat. This is reflected in multidisciplinary studies (e.g., Gudbergsson 1996; Geirsdottir et al. 2009; Vickers et al. 2011), that show that time of initial major disturbance is affected by such factors as climate (mainly cold spells), landscape, elevation, land accessibility (and cost of woodland clearing), and ecosystem stability and resilience, which in turn are affected by soil texture, soil thickness, and the presence of coarse tephra layers. It has been noted that many of the marginal areas such as highland areas were subjected severe land degradation with widespread soil erosion early on (Gudbergsson 1996, 1975; Gudmundsson 1997). Degradation was delayed in many areas of higher resilience such as in the West.

It is worth noting that climate had become cooler leading up to the Settlement, with decline in birch pollen (see e.g., Lawson et al. 2007), making the systems more vulnerable to anthropogenic disturbance. Olafsdottir et al. (2001) concluded that the forest cover and vegetation was already declining at the time of the Settlement because of a cooling trend after 3000 BP that culminated between about 1300 and 1900. The cold Middle Ages were, however, characterized by "broad interval of warmth" with the occurrence of "multidecadal cold intervals," as was determined by investigation of lake sediments (Geirsdottir et al. 2009). The natural systems with limited anthropogenic influence, can adapt to such climate changes and most of the systems would have ample resilience and stability to counter cold spells, with warmer periods in between to enhance recovery. Cooling during the Middle Ages would, however, affect the elevation of the upper limit of continuous vegetation, which became gradually lower (Olafsdottir et al. 2001). The cooling trend would have reduced the stability of the ecosystems with detrimental consequences when human land use increased, especially at marginal locations.

Fig. 12.5 Fate of the woodlands. Continuous heavy grazing by sheep prevents regeneration of the birch woodlands, eventually leading to their disappearance

Grazing in Iceland involved very damaging land use practices such as winter and early spring grazing, which are particularly harmful for declining and marginal ecosystems with low stability and resilience (Fig. 12.5). It has been argued that the grazing capacity of the land had not been exceeded during the Middle Ages judging from total medieval livestock numbers. Such calculations, based on average values for climatic conditions, animal numbers, and vegetation are rather meaningless, as they do not consider ecological principles, including stability, resilience, fluctuating climate, and periodic volcanic impacts. Poor grazing practices were indeed very detrimental: grazing during cold spells and after tephra deposition events is more harmful than grazing during average years in relation to impacts on ecosystems.

The frequent volcanic eruptions have been very destructive for Icelandic ecosystems, with less stable and resilient systems after the Settlement. A good example is found in the Askja area. During the nineteenth century, a growing population led to the establishment of new farms in many marginal areas, such as in the eastern highlands (Jökuldalsheiði). A volcanic eruption in the Askja volcanic system in 1875 lead to the deposition of rhyolitic tephra over the area, with severe erosion following and subsequent land abandonment (Thorarinsson 1979). Volcanic eruptions can also reduce the stability and resilience of systems to repeated volcanic activity, but Dugmore et al. (2007) noted such repeated volcanism as an important factor for the massive destruction in Þjórsárdalur, close to Mt. Hekla, caused by the 1104 and 1300 AD eruptions in the volcano. The largest Hekla eruptions, depositing thick rhyolitic tephra over extensive highland areas, are bound to have caused severe ecosystem disturbance, even during prehistoric times with no land use (Fig. 12.6).

Fig. 12.6 Thick, coarse, rhyolitic Hekla layers in soil (*yellowish*). These layer lacks cohesion and are very susceptible to wind erosion if exposed, causing damage to surrounding systems after erosion processes are initiated. Grains >2 mm in diameter are common and are easily moved by the wind

Fig. 12.7 Unstable ecosystems within the volcanic belt. Much of this area has become a barren desert, with ecosystem remnants surviving in landscape positions providing more resilience (more moisture etc.)

This has been shown to be the case from studies of lake deposits in Hvítárvatn (South Central Iceland) by Larsen et al. (2011), where severe erosion continued for over 100 years after the deposition of the H3 tephra (probably the largest tephra deposition over Iceland during Holocene), dated at about 3100 BP by the authors. However, the land eventually recovered, even in highland areas where the tephra was >10 cm thick. Reduced land use in many areas at present has resulted in evidence of reduced soil erosion. Reduced land use occurred also during the Middle Ages, when the population decreased dramatically because of plagues. Streeter et al. (2012) showed that reduced land use following population decline in the fifteenth century resulted in reduced "geomorphological activity" such as soil erosion.

Climatic variations, mainly cold spells, are often stressed as important contributors to ecosystem collapse in Iceland. Yet, the severity of the "Little Ice Age" is debated (Ogilvie 2005), although the occurrence of cold spells during this time are not disputed. The impact of cold spells would, however, largely depend on the stability and resilience of the systems. Systems under heavy land use would be more susceptible to climatic and volcanic impacts, and the destruction of the woodlands is bound to have an immense impact on the stability of the systems with a change in microclimate. Heavy land use may also mask the impacts of cold spells judging from lake sediments in the Westfjords (Doner 2003), especially in places where the aeolian soil mantle is relatively thin as in that area. Streeter et al. (2012) noted delayed impacts of climate change, attributed to landscape or ecosystem resilience. But one has also to bear in mind that colder climate also means less biological production, which results in increased grazing pressure if animal numbers remain similar, with subsequent reduced food production and consequently this interaction can result in the well-established downward spiral of ecosystem destruction (e.g., Whisenant 1999). The coldest years also saw extensive sea ice at the northern coastlines, blocking fishing harbors and limiting fishing options (see Ogilive and Jonsson 2001) and still increasing the pressure on land-based resources. These authors noted that land use impacts were likely to dwarf the impacts of potential climate change such as the effect of the "Little Ice Age." The question of climate change versus land use effects is very important globally today (see Herrick et al. 2013), with some arguments stating that land use may, in many cases, dwarf the effects of present day man-induced climate change.

The stability of ecosystems varies considerably between geographic regions in Iceland (Figs. 12.7 and 12.8), with wetland soils and more shallow dryland soils far from major aeolian and volcanic sources being more stable than dry thick soils with coarse layers (tephra and aeolian layers). Geirsdottir et al. (2009) noted that erosion had begun around lake Haukadalsvatn in West Iceland prior to the Settlement due to cooling climate, with no sediment spike deposited into the lake soon after the Settlement. This area is characterized by more stable ecosystems than the volcanic zone, with limited wind erosion, and it is still an area with relatively continuous vegetation cover.

Fig. 12.8 Relatively stable and resilient ecosystems in East Iceland, especially the wetlands in the valley. The underlying rock is Tertiary basalts with low permeability leading to high water tables in the area. The dryland positions are evidently more unstable

12.3 Soil Erosion

Soil erosion has long been considered the major environmental problem of Iceland. This prompted a major effort to map soil erosion in the country, which was carried out between 1991 and 1997. The aim of the project was to obtain an overview of soil erosion in all of Iceland, but the extent of the problem was much disputed at that time. The project was run by the Agricultural Research Institute and the Soil Conservation Service of Iceland. The scale of mapping was 1:100,000. Mapping was carried out in the field, with polygons drawn on Landsat five satellite images, and the data was subsequently stored and handled using GIS software. The results were published in the book *Soil Erosion in Iceland* (Arnalds et al. 1997) which was translated into English (Arnalds et al. 2001). Various efforts were made to inform land owners and the general public about the state of the land in relation to the erosion mapping project, including the booklet *To read the land* (Arnalds 1997). The project received *the Nordic Nature and Environmental Award* in 1998. This chapter outlines the methods and results of the erosion mapping in Iceland.

12.3.1 Erosion Forms

Soil erosion processes in Iceland are extremely varied and many processes can occur at any given site. Snow cover and the action of frost are important factors influencing the erosion, including needle ice formation (see Chap. 10). Conventional models for soil erosion, such as the Universal Soil Loss Equation (USLE) and the Wind Erosion Equation and similar models are poorly suited for Icelandic conditions except perhaps for the desert areas. Conventional methods are largely designed for cultivated areas and are often poorly suited for rangelands in general (e.g., SRM 1992; NRC 1993; Pierson 2000). A geomorphological approach was taken for designing methods for Icelandic conditions. Soil erosion forms were defined based on features that can be identified in the field. These forms are broadly divided into two categories: (i) forms associated with erosion of soils with vegetation cover (Andosols), and (ii) erosion on deserts, Vitrisols (vitric soils of the deserts, see Sect. 6.5), Leptosols etc. (Table 12.1).

Table 12.1 Classification of Icelandic erosion forms (Arnalds et al. 2001)

Erosion forms associated with erosion of vegetated land	Erosion associated with desert landscapes
Advancing sand fronts	"Melur" (lag gravel /till surfaces)
"Rofabards" (escarpments)	Lava surfaces (without sand or soils)
Erosion spots	Scree (gravelly/rocky hillsides)
Erosion spots on solifluction slopes	Sandur (aeolian and tephra sand surfaces)
Landslides	Sandy lag gravel
Water channels (rills and gullies)	Sandy lavas

The Icelandic soil erosion survey system includes grading of erosion severity, with a scale of 0–5 as follows: 0: no erosion; 1: little erosion; 2: slight erosion; 3: considerable erosion; 4: severe erosion; and 5: very severe erosion. Areas with erosion severity 4 and 5 are not considered suitable for grazing until erosion has been halted. Following is a discussion on these different erosion forms with examples illustrated. Examples of the erosion severity grading are also illustrated with some of the photographs.

12.3.2 Advancing Sand Fronts (Encroaching Sand)

Advancing sand fronts form where there is a source of loose silty and sandy sediments that are carried by the wind over vegetated areas. A tongue-shaped front into the vegetation cover is created, where sand is advancing (Fig. 12.9). The soil materials underneath the destroyed vegetation are added to the silty/sandy materials that keep advancing with prevailing dry winds. A barren desert is left behind. If the soils are very sandy, e.g., if they have thick coarse tephra layers, the soil materials added to the process along the way of the front are sufficient to maintain the process; the tongue continues until the advancement is stopped by some landscape features such as a hill, river, or a shoreline. Continuous activity with advancement of the front is also maintained if there is a steady source of aeolian materials, such as are deposited by repeated flooding of glacial rivers or from glacial lakes with unstable shore lines. Advancing sand fronts are common on and near the volcanic active zone, and the remnants are expressed as long straight lines on the landscape on the boundary between vegetation and desert, in the same direction as the dry winds, from the abrasion of the silt/sand along the vegetation–desert boundary.

Fig. 12.9 Example of the formation of an advancing sand front. The original source of the sand (and silt) is sediments half filling the lake due to water erosion in the surrounding area, drying out the lake. The sediments are driven to the south (*left* on the fig. 12.9) with north prevailing dry winds

There is evidence that this type of erosion has been the most destructive erosion form after the Settlement. Advancing sand fronts can progress over vegetated areas up to several hundreds of meters each year if there are a lot of sandy and silty materials advancing. There are accounts of such rapid advancement in Northeast Iceland, where the sediment sources vary from river sediments (Jökulsá á Fjöllum, see Fig. 12.10), to unstable ephra and glacial deposits.

The Icelandic Soil Conservation Service was established as *Sandgræðsla ríkisins* in 1907, mainly to battle advancing sand, which was destroying farm after farm in South Iceland. An account of the battle against the sand is given in several papers in a book commemorating the 50 years anniversary of the Soil Conservation (Sigurjonsson 1958; in Icelandic), but the history is also accounted for in the 100 years story of soil conservation in Iceland (Olgeirsson 2007; in Icelandic) which in part was used as the basis for an book in English by Crofts (2011): *Healing the Land*.

Areas that are subjected to sand abrasion from sand sources, or possibly subjected to such stress, like the areas within the volcanic zone, can be described as supermarginal areas, where it is very important to maintain as strong vegetation cover as possible, preferably birch or salix woodlands/shrublands, which alter wind conditions at the surface and accumulate and store snow cover. Many of these areas are now protected from grazing, but recovery of sandy deserts is very slow because of the unstable sandy surfaces (see subchapter on restoration later on).

12.3.3 Rofabards

"Rofabards" may be the most typical of all the Icelandic soil erosion features and most noted by observers. Rofabards are escarpments marking the boundary between vegetated systems on top with a mantle of Andosols formed in aeolian and tephra materials, but a barren surface at the bottom and in the adjacent area; typically till, lava or a sandy surface. Rofabards are often very prominent features on the landscape (Fig. 12.11) and were the subject of discussions by Arnalds (2000). The vegetation and the root mat provides a cohesive upper surface, but underneath are less cohesive soil materials which are undermined by erosion processes (Fig. 12.12). Conditions for the formation of rofabards are found in dryland areas where the aeolian soil mantle is relatively thick, which is within and near the active volcanic zone and close to glaciers. The thicker and coarser this aeolian soil mantle is above the harder bedrock, the more active the rofabards become in terms of erosion.

Fig. 12.10 Infrared satellite image of a portion of Northeast Iceland showing the path of many advancing sand fronts. Vegetation is *red* on the image, but the deserts *dark-bluish*. Lake Mývatn is at the *bottom left*. Note the *straight lines* on the sides of the path of the fronts. New lava (1980s) from the Krafla system shows up *black* on the *center left*. The river in the *upper right corner* is Jökulsá á Fjöllum, the major river of NE Iceland. Eruptions in volcanic systems under Vatnajökull ice cap causes catastrophic flooding which deposits large amount of sediments and which are later subjected to wind erosion and the creation of advancing sand fronts. The Hólsfjöll desert was created by such process during the Middle Ages, the formation aided by reduced stability of the systems due to land use. A desert area NW of Lake Mývatn originates in sandy deposits near the lake. Numerous smaller advancing sand fronts are east (*right*) and north of Lake Mývatn. SPOT 5 Satellite image © EruoImage

Measurements show that the rofabards are retreating (the boundary between desert and vegetated areas are moving into the vegetated land) at rates ranging from few millimeters to >50 cm year^{-1}. It should be noted, however, that much of the most erosion susceptible soils have already been lost, and rates of soil loss were rapid during the main erosion phases of the Middle Ages.

Many soil erosion processes occur at rofabards. Wind erosion is common, especially in NE Iceland and where the soils are thick and coarse. Water erosion is important for

Fig. 12.11 Rofabards are often quite prominent in the landscape within the volcanic zone and close to active aeolian sources (creates thick Andosol mantle), but they were more abundant in older days during the main erosion phase of the Middle Ages

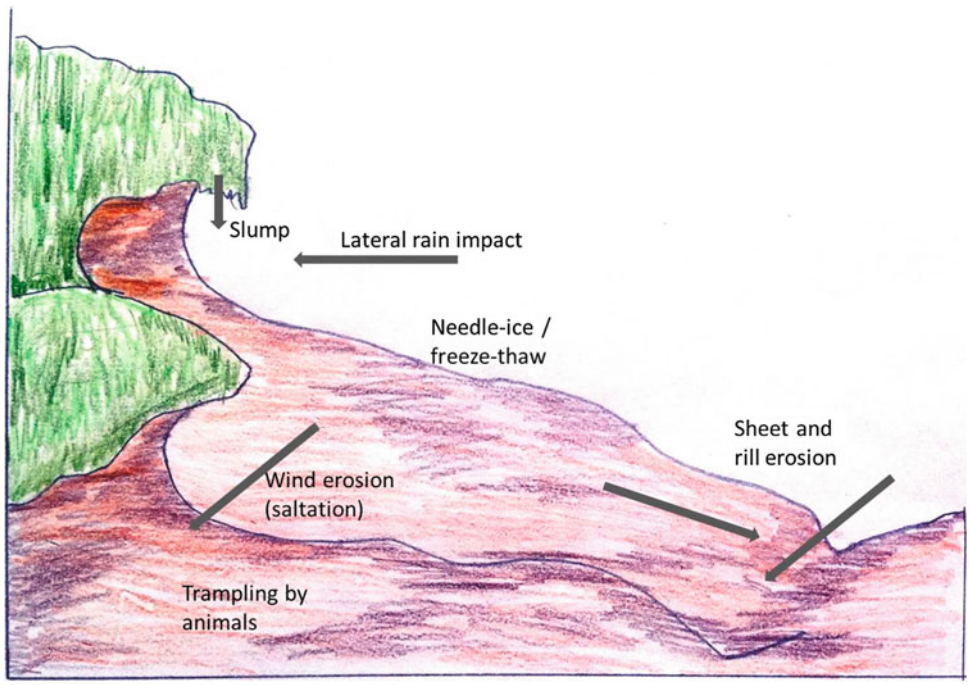

Fig. 12.12 Erosion processes that can be expected at rofabards

rofabards in South Iceland. Lateral rain, during high intensity winds is a key factor contributing to the erosion of rofabards as well as to erosion of desert surfaces (see Figs. 12.12, and 12.13). As the rofabards become undermined, the surface turf mat slumps down. Sheep seek shelter under the rofabards, and trampling by the animals also contributes to the erosion.

12.3.4 Erosion Spots

Erosion spots are small patches of barren soils in otherwise vegetated surface (Fig. 12.14) which typically is relatively flat. They are extremely common in the Icelandic rangelands, and are usually the result of overgrazing, at least when they occur in the lowlands. Vegetation re-establishment is

Fig. 12.13 Lateral rain splash during one high intensity storm has cut into the ground but small pedestals are protected by the pebbles. Large rain drops driven by 20–40 m s^{-1} gale force winds have a substantial erosion power. Grass straws at *top* and the *bottom right* give the scale. *Photo* © Elin Fjola Thorarinsdottir

Fig. 12.14 Erosion spot are barren patches in otherwise vegetated land. They are most often a result of overgrazing, especially in the lowlands. The vegetation here is degraded poor heathland and land covered with moss, with low abundance of grazing plants, which have been grazed out over the years

slow after the erosion spots have formed. Conditions for needle-ice formation are optimal within the spots, which impede vegetation establishment in the spots by killing little seedlings that get established during summer. Recovery, after prevention from grazing, can take many decades.

12.3.5 Hill Slopes: Solifluction, Water Channels, and Landslides

Hill slopes are subjected to slow downhill movement of the soils, which is termed "solifluction". Solifluction leads to the formation of wave-like system of small terraces ("steps") or

Fig. 12.15 A front of a solifluction lobe with erosion spot which is caused by overgrazing by horses. Erosion can develop into a severe problem on such slopes

tongue-shaped lobes (Fig. 12.15). Erosion spots that form on such slopes are subjected to the force of running water, which is a minimal factor for erosion spots on flat land. Therefore, they are a separate entity in the Icelandic soil erosion classification system. Erosion spots on hill slopes are often easier to see looking down the slopes, and can be pronounced even though the hill looks full vegetated looking up the hill (Fig. 12.16).

Water channels occur on many vegetated hill slopes, but often develop to form rofabards as the erosion progresses on slopes with thick aeolian soil mantle. Hill slopes are most common in the valleys of the Tertiary lava stack landscapes of Iceland. Slope length is often limited by each lava flow in the stack, making water erosion not as serious as it would be if the slopes had continuous surfaces. Palagonite formations (hyaloclastites from Quaternary volcanism, see chapter on geology) tend to have long continuous convex slopes. They are periodically subjected to intense water flow and are frequently lacking vegetation cover, but may often have had

Fig. 12.16 Looking down solifluction slopes reveals the erosion spots, which are not prominent when the view is from *below*. This slope looks fully vegetated looking up the slope

Fig. 12.17 Soil and vegetation remnants on otherwise barren scree slopes in the Westfjords. Many of the barren hill slopes of Iceland were in part vegetated prior to the Settlement. Vegetation recovery on these kinds of slopes is extremely slow, especially on rhyolitic scree slopes

such cover prior to use of the land. Such vegetation and soil cover may have been lost early on after the Settlement, but remnants of these ecosystems can be found on many of the eroded hillsides (Fig. 12.17).

Landslides are common in Iceland and they sometimes cause damage to buildings, roads, and other structures. The reason for the high frequency of landslides is the noncohesive Andosols and periodic overloading of water. The soils can adsorb very large quantities of water and some become thixotropic upon reaching the liquid limit. Large mudslides can occur where conditions lead to saturation of the soils, such as during snow melt in spring (Fig. 12.18). It seems that both tephra layers in the soils and the bedrock underlying the aeolian soil mantle can provide slip planes that further increase landslide susceptibility.

Fig. 12.18 A large landslide in N Iceland, formed by oversaturation of water uphill and the soil reaching the liquid limit

12.3.6 Erosion Associated with Desert Landforms

The Icelandic desert systems cover over 40 % of the island and they are subjected to erosion by wind, water, hill slope process, and cryoturbation. Desert ecosystems were discussed in Chap. 4. Soil classification of desert soils was discussed in Chap. 6, and soil properties (Vitrisols) in Chaps. 7–9. The surface types of Icelandic deserts were classified and mapped during the "Soil Erosion Mapping Project" that provides the basis for this subchapter (Arnalds et al. 1997, 2001). As was stated previously, the Icelandic erosion classification considers soil or surface stability with scores from 0 to 5 (no erosion—extremely severe erosion). The desert types are **lag gravel surfaces** (glacial deposits dominate), **sandy surfaces** (fluvial and aeolian deposits dominate), **barren lava surfaces,** and **scree slopes**. As aeolian processes carrying silt and sand over various surfaces are such a dominant feature of Icelandic nature, subclasses with **sandy lag gravel** and **sandy lavas** are special classes in this classification (see Chap. 11 on the aeolian

Table 12.2 Desert surfaces in Iceland

Desert surface	Erosion score					Total
	1	2	3	4	5	
	km^2					
Lag gravel	9,939	8,546	6,580	0	0	25,065
Lavas	1,832	228	25	0	0	2,085
Sandur	195	337	318	1,087	2,828	4,765
Sandy lag gravel	8	741	5,407	6,217	1,286	13,659
Sandy lavas	10	101	1,366	1,757	1,620	4,855
Scree slopes	64	913	2,378	1,255	392	5,002
Bare brown soil	17	518	350	65	36	987
Total	12,065	11,384	16,424	10,381	6,162	56,418

More than one desert type can occur within the same mapped polygon; hence the total area in the table is considerably higher than the actual value

environment). The results of mapping of the deserts are presented in Table 12.2 and Fig. 12.19.

Lag gravel surfaces are the most common desert surfaces, extending about 25,000 km^2, but much of these surfaces occur in combination with vegetated land, hence the nearly 10,000 km^2 with erosion score 1. The lava surfaces are also rather stable unless sandy deposits have been blown onto such surfaces. The sandy surfaces have high erosion scores (very unstable surfaces), and they occupy >20,000 km^2, as the surface types sandur (sand-flats), sandy lag gravel and sandy

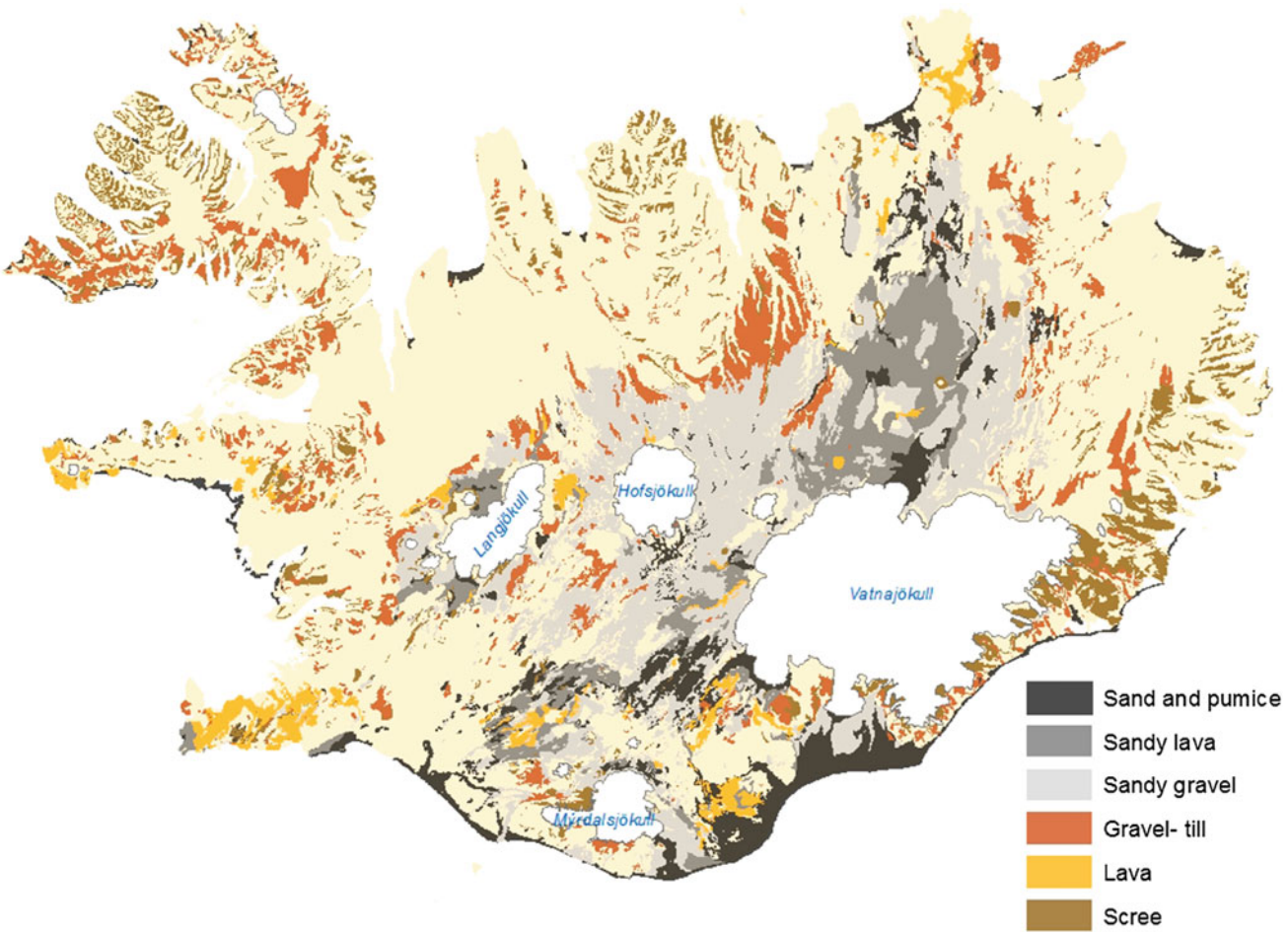

Fig. 12.19 Map showing the extent of desert surfaces in Iceland. Modified from Soil Erosion in Iceland (Arnalds et al. 2001), prepared by Sigmundur Helgi Brink, © OA/SHB, AUI

lava areas. A large proportion of Holocene lavas have sandy deposits in the surface (4,855 km^2). Scree slopes are quite common with >5,000 km^2. It should be noted that each unit or polygon under this mapping scheme can have several erosion scores (e.g., both sandy lag gravel and sandur occurs within the polygon), resulting in a total of 56,418 km^2 area mapped as desert, but the total area of deserts is about 40,000 km^2 according to the Nytjaland database (see Chap. 4).

Most of the desert areas continue to be grazed, in spite of the negative impact of such land use practice on these collapsed and/or vulnerable ecosystems.

12.4 Wetland Disturbance

For ages, wetlands provided grazing areas, they were important for hay production and some provided peat for fuel and turf for house structures (Magnusson 1998). Yet, wetlands also were obstacles to the traveler and they were, in a sense, considered a negative aspect of the landscape in older times. Draining the wetlands facilitates oxidation of the organic matter and release of nutrients, resulting in substantial increase in biomass production (Magnusson 1998), a prospect that was of interest to the farming community during the early twentieth century.

After World War II, with the arrival of large and effective digging machinery, a large scale program to drain the wetlands was initiated (Fig. 12.20). This draining program was a part of the national post-war strategy to ensure food safety (Gardarsson et al. 2006). In the early stages of the drainage effort (1940–1965), the drained areas were mainly used to establish permanent hay fields for the production of winter fodder for cattle and sheep (see Helgadottir et al. 2013). During later stages of the effort, the focus was on creation of rangeland. Currently, less than 15 % of the drained areas are used for agricultural purposes as hay fields or for growing grain. The Agricultural University of Iceland (unpublished data) has mapped and measured the length of the drainage ditches to be >30,000 km, with >3,500 km^2 wetland area converted to grassland (Hallsdottir et al. 2013). It has been estimated that 50–75 % of all wetlands in lowland areas have been altered and disturbed (Oskarsson 1998; see also Thorhallsdottir et al. 1998) (Fig. 12.21).

The drainage of these wetlands has resulted in large scale greenhouse gas emissions as the organic matter oxidizes; a release of greenhouse gases of the same order of magnitude as emissions by the heavy industry (smelters) in Iceland (Oskarsson 2008; Gislason 2012; Hallsdottir et al. 2013). The majority of the drained wetlands are not used for hay production and some even not for grazing. It can be inferred by the published literature (Geirsson 1998; Oskarsson 1998; Magnusson 1998; Wald 2012; Olafsdottir 2013) that some were drained simply because of generous financial aid provided for the effort, especially after 1974, and that the vast majority of wetlands drained after 1966 are generally not in use as hay fields.

Fig. 12.20 Drainage ditch being put in a wetland in the South. The ecosystem changes towards a grassland, but a large amount of CO_2 is released by oxidation of the organic rich wetlands. *Photo* © Hlynur Oskarsson, AUI

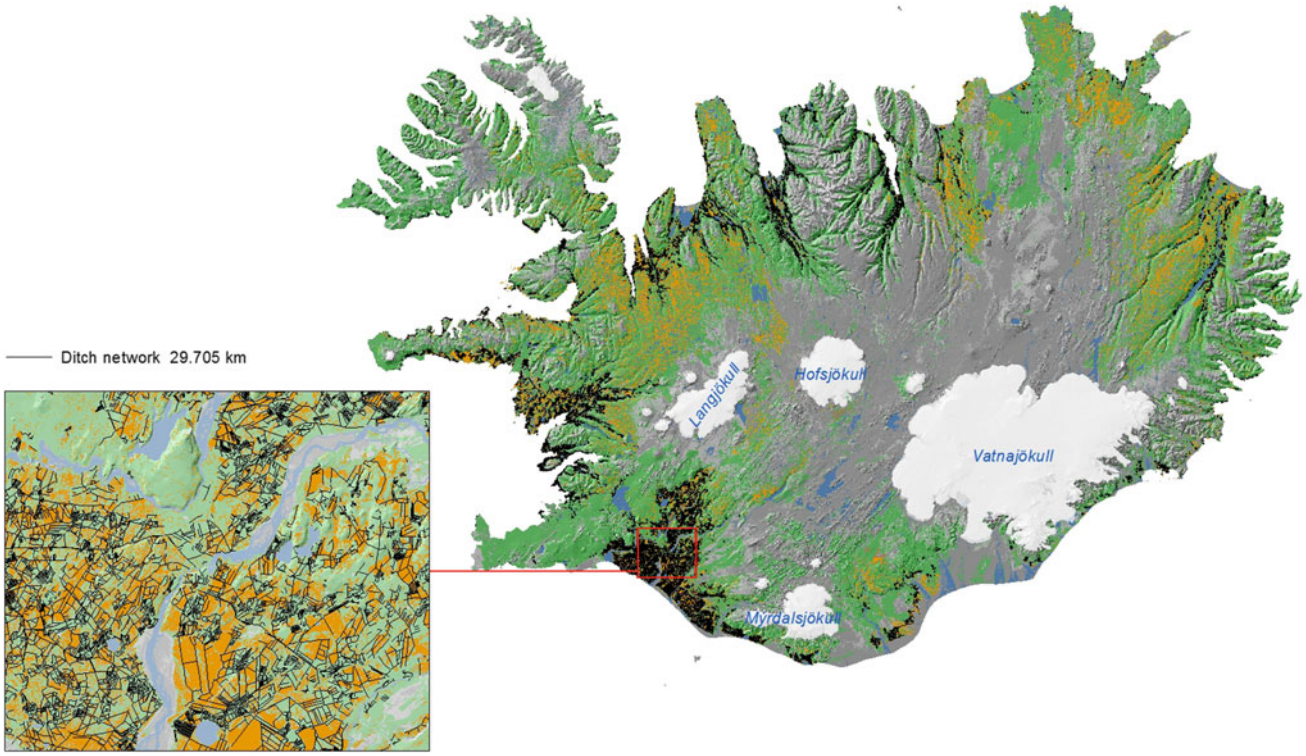

Fig. 12.21 Wetland disturbance by drainage. The wetland areas are shown in *red* and *pink colors*, but the drainage ditch system has been superimposed as *thin black line* following each ditch. The figure clearly indicates that much of the Icelandic lowland wetlands have been disturbed. A portion of the map is enlarged, to give an indication of how ditches dominate many of the wetland landscapes. *Image* Icelandic Farmland Database (vegetation classes) and the IGLUD database (drainage ditches), prepared by Sigmundur Helgi Brink. © SHB/JG/OA, AUI

Wetland restoration has begun in Iceland and will likely grow in importance during the next decades. However, some of the drained wetlands are still very important for agriculture and will in all likelihood continue to be used as such.

12.5 Reading the Land—A Simple Scheme for Land Condition

12.5.1 A Simple Land Condition Scheme

The observer of Icelandic landscapes, native or foreign, may believe that the beautiful Icelandic landscapes are pristine and unspoiled by human actions. The observer may not comprehend the vast changes that Icelandic landscapes have undergone since the Settlement of the country. Some efforts have been made to prepare materials to aid the public in understanding the state of Icelandic ecosystems. Arnalds (1997) published an educational booklet titled *To Read the Land* and Arnalds and Aradottir (2014) recently published a book in Icelandic (*To Read and Heal the Land*), where an attempt is made to explain for the public ecosystem disturbance and the condition of the land. These publications draw from many sources, including the "Erosion Mapping Project" and a paper published in the Soil Conservation Yearbook on assessment of land condition in Iceland (Aradottir et al. 1992). The methods presented by Aradottir et al. (1992) which are used here were in part adopted and modified by Archer and Stokes (2000) and Bestelmeyer et al. (2011) for rangelands in general and by Thorsson (2008) for an Icelandic desertification research study. Following is a short discussion on the classification land condition in Iceland, based on the original Aradottir et al. (1992) system to aid the reader in understanding the Icelandic landscapes.

Aradottir et al. (1992) split land condition into six stages, ranging from pristine (Stage I) to deserts (Stage VI) (Fig. 12.22). There are dramatic differences from the pristine stage to the desert for most ecological variables. Table 12.3 lists some of the key surface and soil parameters with grading (A–E) of surface parameters and a numerical range for three soil parameters to give an indication of the dramatic changes in ecosystem functions. The discussion below is mainly aimed for dryland systems below 300–400 m elevation.

I. **The pristine stage** is characterized by woodlands and rich heathlands with grasses and herbs (Fig. 12.23). The soils are Brown Andosols with fertile soils.

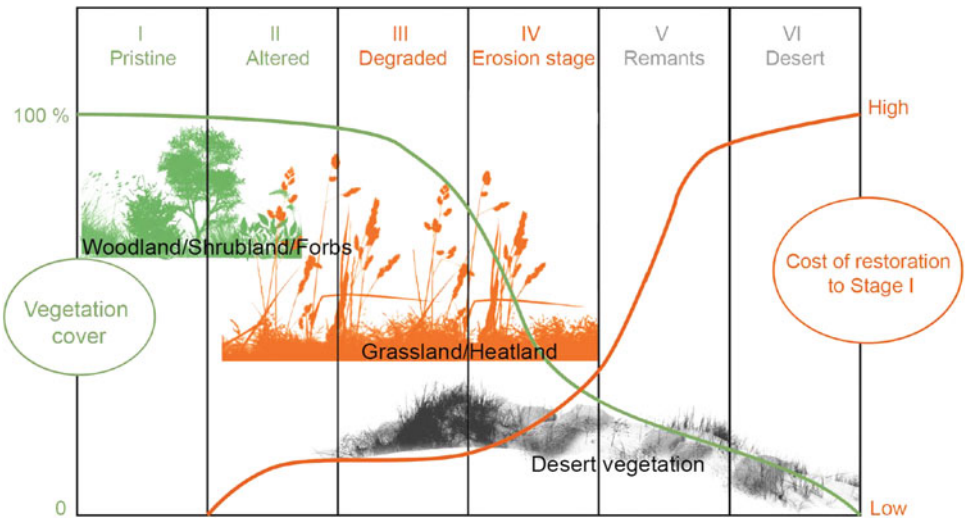

Fig. 12.22 Land condition classes, vegetation cover and cost of ecosystem restoration to Stage I. Adopted from Aradottir et al. (1992) and Arnalds and Aradottir (2014)

Table 12.3 A gradient for dryland condition for factors typically used applied to assess land condition or quality

	I. Pristine	II. Altered	III. Degraded	IV. Erosion	V. Remnants	VI. Desert
Surface						
Plant cover (%)	A full	B	C	D–E	E	E non
Surface wind	A non	B	D	E	E	E extreme
Litter	A high	B	C	D	E	E non
Snow accumulation	A high	B	B–D	D–E	E	E non
Wind erosion	A non	A–C	B–D	C–E	C–E	C–E extreme
Water erosion	A non	A	B–C	C–E	C–E	C–E extreme
Needle ice formation	A non	A	B	C–D	E	E extreme
T° extremes	A non	B	B–D	C–E	E	E extreme
Evaporation	A limited	B	C	D–E	E	E extreme
Infiltration winter	A ample	B	C–D	D–E	D–E	E limited
Topsoil						
C% in top 30 cm	6–12	3–7	1.5–4	0.5–3	0.2–2	0.0–0.5
N top 30 cm, kg/ha	>10,000	>5,000	>2,500	<1,000	<500	<250
Clay%	15–30	10–25	10–20	3–15	3–10	1–5

Descriptive terms (non, low, considerably, high, very high) or typical numerical values or ranges. Note that moss and poor heathland may also occur as successional stages, e.g. on disturbed ground (lava, ash, floods) or as a result of restoration efforts

Erosion is negligible, the system has favorable microclimate with limited surface wind speeds and snow is trapped in winter for insulation and better moisture conditions. Infiltration is considerable in winter. Carbon contents are high, exceeding 6 % in surface horizons with ample nitrogen stocks and robust nutrient cycling.

II. **The altered stage** is characterized by systems that have been modified by land use, without causing severe land degradation (Fig. 12.24). The shelter from the woodland is lost, allowing for more effects of cryoturbation with increased formation of hummocks. Productivity is lower with less amount of nutrients (carbon, nitrogen) in the system compared to Stage I. Erosion is still low.

III. **The degraded stage** is often characterized by hummocky landscape (Fig. 12.25) with systems with high proportion of mosses and poor heathlands (see Chap. 4 on vegetation classes). Microclimate is unfavorable with intense cryoturbation. Litter accumulation is limited and physical surface characteristics are notably more unfavorable than at Stages I and II, with reduced infiltration in winter and surface runoff during snowmelt events. There is more erosion activity and more coarse materials being deposited on top of the soils, leading to lower C, N, and clay contents in surface horizons.

Fig. 12.23 Stage I. Pristine. A typical woodland provides good shelter, and robust nutrient and water cycles. Soils are rich in organic carbon with favorable soil properties and good infiltration the year around

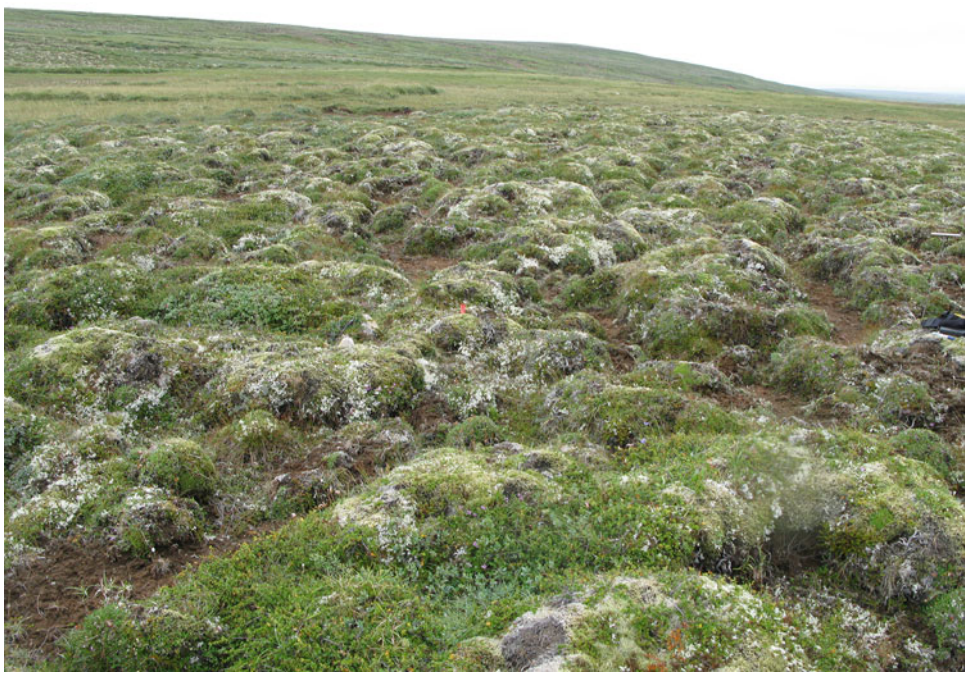

Fig. 12.24 Stage II. Altered and somewhat degraded stage. The carbon pool is lower with less robust nutrient cycles. Little shelter from the wind and there is pronounced cryoturbation with thufur formation. Water is lost with blowing snow and with impeded infiltration in winter. Some erosion spots visible on the landscape. Species composition has been altered by selective grazing, with less palatable species becoming more abundant than grasses and forbs

IV. **The erosion stage** is characterized by a mosaic of two systems: vegetated areas and barren patches where erosion has removed the aeolian soil mantle (Fig. 12.26). The vegetated areas have the characteristics of degraded areas (Stage III) and the barren areas have the features of desert surfaces. Erosion is quite rapid at this stage.

V. **The remnant stage** is characterized by the deserts of Stage VI, yet there are remnants of previous ecosystems (Fig. 12.27). These remnants bear similarities to systems at Stage III (degraded), but with lower nutrient reserves due to aeolian and fluvial deposition of coarse materials. The remnants are often important sources of

Fig. 12.25 Stage III. The degraded stage. Considerable amount of soils has been lost together with vegetated systems, with barren patches becoming prominent on the landscape. Active erosion. The soil properties of the barren areas are poor compared to the vegetated patches. The area shows some signs of improvement with reduced grazing intensity with relatively vigorous plant growth on the vegetated patches

Fig. 12.26 Stage IV. The erosion stage (late in the stage); soils and vegetation are lost at a rapid rate. The rofabards show signs of high erosion activity. The soils here are coarse grained and especially susceptible to wind erosion

plant materials to spread around the surrounding desert during restoration efforts.

VI. **The desert stage** is the final stage of the degradation (Fig. 12.28). The soils are Vitrisols (Sect. 6.5) or Leptosols. Plant cover is often 5–15 %. Here is no shelter from the wind, the desert surface heats up during summer leading to very rapid evaporation, but there is very limited infiltration of water during winter. This leads to intense surface runoff during high intensity snowmelt events in winter. In summer, the sandy areas are subjected to intense wind erosion events (see Chap. 11 on aeolian environments). The soils are coarse with limited nutrient reserves and low water holding capacity compared to the vegetated systems.

Fig. 12.27 Stage V. The remnant or vegetation island stage. Vegetation and soil remnants indicate lost ecosystem riches. Deserts dominate the landscape, with lack of energy input (photosynthesis), poor nutrient cycling (soil biota, carbon, and nitrogen) and disrupted water cycle. Desert surfaces are shaped by the geology of each area, such as lavas, sandy surfaces, scree slopes, and gravel. The islands are important sources of plant materials for spreading during restoration efforts

Fig. 12.28 Stage VI. The desert stage. All the previous soils and vegetation cover has been lost. Vitrisols, poor in nutrients and with disrupted water cycle remain (see Table 12.3 for changes in soil and surface parameters). Extreme surface conditions with excessive evaporation in summer but concrete ice and limited infiltration in winter

12.5.2 Condition of Communal Grazing Areas

The Erosion Mapping Project resulted in an assessment of all Icelandic communal grazing areas (Arnalds et al. 1997, 2001). The grazing commons are typically 400–1,000 km^2. There is a large difference in condition between the commons. Some have reasonably good vegetation cover (>80 %), often characterized by poor heathland and sometimes wetlands. The communal areas rated in poor condition often have less than 50 % vegetation cover and severe erosion (erosion grades 4 and 5) on >50 % of the land. Yet, almost all these areas are still used for grazing, regardless of their condition. Most of these poor-state commons are within or in the proximity of the active volcanic zone.

An attempt is made to visualize the changes that have occurred within the barren communal grazing areas in Fig. 12.29. It shows parts of two communal areas in NE Iceland, divided by the glacial river Skjálfandafljót at the

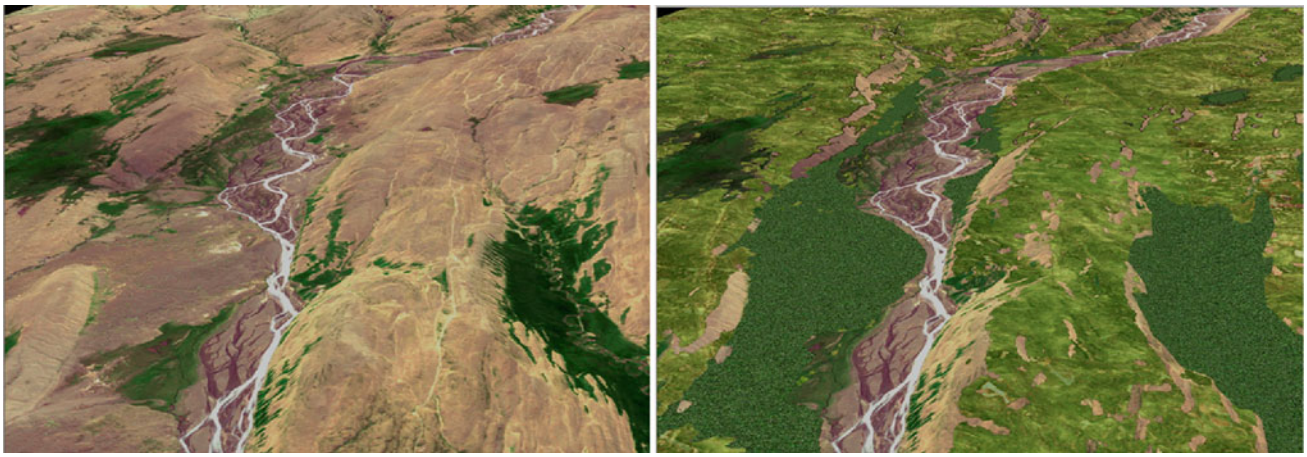

Fig. 12.29 Now and then. A satellite image showing the current vegetation cover (on the *left*) and possible vegetation cover about 200 years after the Settlement (on the *right*) in two communal areas in NE Iceland. The river is the glacial river Skjálfandafljót. The vegetation cover on the right has been added to the original image. There is a dramatic difference between the current state and the expected vegetation cover in the past. The area can be restored to the former condition, but a long time is required (possibly 50–200 years, depending on inputs such as fertilizers and planting) with initial protection from grazing. Image processing based on SPOT (© EuroImage) by AUI/SM. © OA/SM; AUI

center with a perspective looking inland (south). The figure on the left shows the current condition with scattered vegetation patches in depressions. A road winds into the interior on the right (west side of the river). The two commons shown on the figure are among the poorest vegetated commons, but both are still used for grazing. On the figure on the right, an attempt has been made to add vegetation cover to the land, to resemble the condition about 200 years after the Settlement. The area is almost fully vegetated with some erosion on the steepest parts of the landscape. Birch forest dominates the valleys. This land could support a high number of grazing animals without damaging the environment, with good grazing practices. The difference is quite dramatic.

The Soil Conservation Service has protected many severely degraded areas from grazing, but there is a growing pressure to return grazing on some of these areas, even though they are in a poor state and mostly deserts. This shows the need for improving environmental education and communication in Iceland, and the need to tailor environmental law more to ensure protection and the restoration of severely degraded ecosystems.

12.6 Erosion Control and Restoration Perspectives

12.6.1 Early Efforts and Drivers for Restoration

Realization of the severe degradation and soil erosion was part of the "Enlightment" of the late nineteenth century, with advancing sand fronts being a constant threat to many communities. Organized efforts began in the Westfjords in the late eighteenth century by the priest Björn Gunnlaugsson, where calcareous beach sand was advancing into a small agricultural valley. There are accounts of sand burying farms in NE Iceland from the late eighteenth century (Crofts 2011). Earlier attempts to halt sand drift are manifested in old structures to halt sand drift, but they are poorly accounted for (Crofts 2011). Encroachment of sand from the Thjorsá river and the Hekla tephra deposits caused a massive destruction of one farm after the other in the late nineteenth and the early twentieth centuries in South Iceland. In 1907, while Iceland was under Danish rule, an organization was established to halt the sand and to protect and re-establish the tree cover. The Danish had successfully halted sand drift and re-established tree cover in severely degraded areas in Denmark (see Sigurjónsson 1958; Arnalds 1988; Olgeirsson 2007; Crofts 2011). There were only small patches of tall birch forests remaining in Iceland at that time, which were saved at the "last minute." At that time, Iceland was among the poorest nations anywhere on Earth, with rapid population growth, scarcity of food and fuel, and escalating land degradation problems. This organization that was established in 1907 developed into the current Soil Conservation Service (initially as the Sand Reclamation Service) and the Forest Service of Iceland. Thus, Iceland hosts one of the world's oldest operating national Soil Conservation agencies, while most other national agencies where established after the US Soil Conservation Service was initiated in the 1930s.

Halting the sand drift was the initial driver of the restoration work in Iceland as reviewed in a recent paper by Aradottir et al. (2013). The early efforts to halt the sand

encroachment gradually became more and more successful during the twentieth century. Lyme grass (*Leymus arenarius*), a native sand-tolerant species, was (and still is) widely used to stabilize the sand, but various materials such as rocks and corrugated iron were used to raise wind brakes (Olgeirsson 2007).

Halting soil erosion was a major emphasis of the Soil Conservation up to the end of World War II, but after the war there was a growing emphasis on establishing new vegetation areas to enhance agricultural production, mainly grazing areas for sheep (Magnusson 1997; Petursdottir and Aradottir 2011). The latter part of the twentieth century saw increasing emphasis on "paying the debt to the land" (idealistic reasons for restoration work), but ecological restoration and nature conservation are currently growing as drivers for reclamation projects in Iceland (Aradottir et al. 2013). Other drivers include carbon sequestration in soils and vegetation to meet national commitments in relation to the UN Framework Convention on Climate Change (Petursdottir and Aradottir 2011; Aradottir et al. 2013).

12.6.2 Revegetation—Restoration

The terms "restoration" and "ecological restoration" have been defined in several different ways (see Aradottir and Hagen 2013 about restoration concepts and definitions) but the terms can be perceived as actions to facilitate the recovery of damaged or degraded ecosystems, to similar ecological function as existed before disturbance or degradation of a system. The terms "reclamation" and "revegetation" have more general meanings and involve actions to establish vegetation cover and ecological function on the surface. All these terms have frequently been used in relation to efforts to halt erosion and/or to restore degraded land and deserts in Iceland to productive ecosystems. Icelandic has a unique term "landgræðsla" which literarily means "land-healing," which is used in the Icelandic name of the Soil Conservation Service ("Landgræðslan"). This term is often used for all actions taken to improve the condition of the land, including protecting degraded lands from grazing. The Icelandic term for ecological restoration is "vistheimt."

Aradottir and Halldorsson (2011) edited a comprehensive volume on ecological restoration in Iceland ("Vistheimt á Íslandi," in Icelandic), including a review of restoration projects and the history of restoration efforts. The history of soil conservation in Iceland, including halting soil erosion and reseeding was published by Olgeirsson (2007) in Icelandic, rewritten in part in English by Crofts (2011). Other overviews available in English include those of Runolfsson (1987), Arnalds et al. (1987), Magnusson (1997), Aradottir and Eysteinsson (2005), and Aradottir et al. (2013).

There is considerable research that has been carried out over the years in relation to restoration efforts in Iceland. A long list of research projects with about 250 cited references was published by Aradottir et al. (2011) in the book "Vistheimt á Íslandi" (Ecological Restoration in Iceland). Early research focused on fertilizer experiments and finding suitable grass species for seeding in desert areas, both native and introduced, first with the intention to create fodder for sheep, but later increasingly to provide initial surface stability to allow natural establishment and succession of native species (see Magnusson 1997; Aradottir et al. 2013). Succession was studied on the newly formed Surtsey volcanic island (e.g., Kristinsson and Heidmarsson 2009; Magnusson et al. 2009), in lavas (e.g., Cutler et al. 2008), and on recently formed moraines in front of retreating glaciers (e.g., Marteinsdottir et al. 2010). A growing body of research in relation to reclamation and restoration has emerged over the past 30 years (Arnalds et al. 1987; Elmarsdottir et al. 2003; Gretarsdottir et al. 2004). These studies are not limited to vegetation cover, but also deal with soils and factors such as arthropods (e.g., Oddsdottir et al. 2008). New ecological methods to restoration involving sward and turf transplants have recently been studied at the Agricultural University of Iceland (e.g., Aradottir 2012; Aradottir and Oskarsdottir 2013).

Multidisciplinary research in relation to reclamation projects was initiated in the 1990s on the Blanda reclamation areas in NW highlands, where barren areas were being reclaimed to substitute foodstuff for grazing when a large hydroelectric reservoir was created in the area (see Arnalds et al. 1987; Thorsteinsson 1991; Gudmundsson 1991). More recent large reclamation and restoration ecology research projects, with specific studies of soil parameters include the LandAid and CarbBirch projects and studies by the Icelandic Soil Conservation Service on carbon sequestration within reclamation areas. The LandAid research area is unique for its extent, with 40 research plots, each being 1 ha, located within a 350 ha area dedicated to this research (Fig. 12.30). The research was initiated in 1999 with 10 commonly applied reclamation treatments, replicated four times (see Arnalds et al. 2013).

12.6.3 Reclamation and Soil Development

An important element of restoring ecosystems is renewing soil functions, such as organic carbon content, nitrogen and other nutrient levels, water infiltration, water holding capacity, and reducing evaporation. The results from these reclamation studies show in general a reversing of the trends

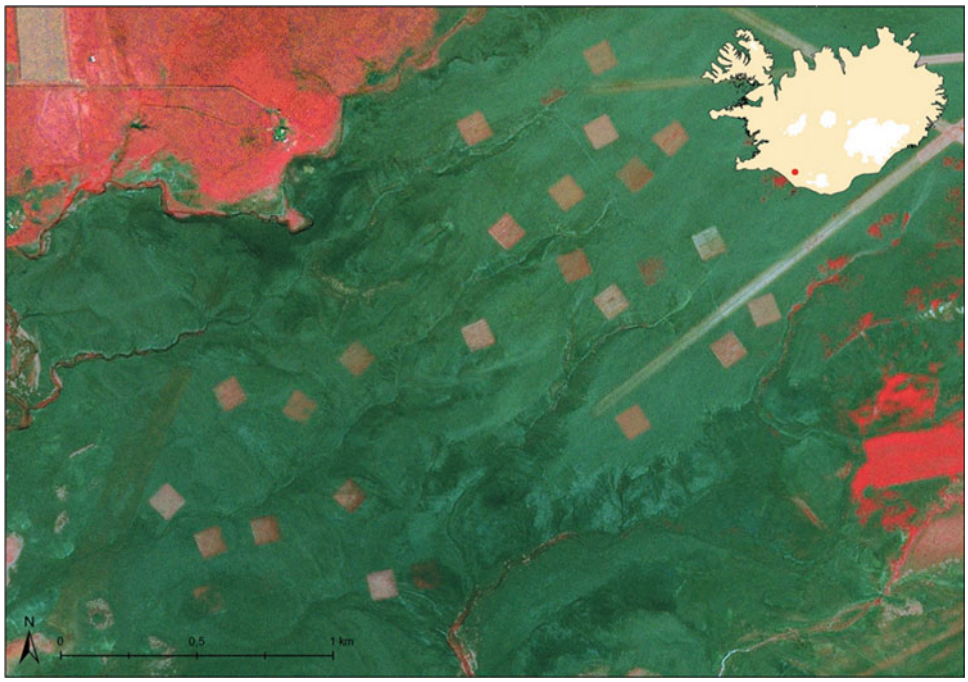

Fig. 12.30 The Geitasandur Landaid Restoration Research Area, infrared satellite image showing vegetation as *red*. The 1 ha plots show up as *squares* on the image. *Satellite image* © CNES/SPOT Image Corporation 2003

for the soil and surface factors in Table 12.3. Carbon accumulates in the soil at a relatively rapid rate of 0.04–0.08 kg C m^{-2} $year^{-1}$, owing to the andic nature of the soils, fast weathering rates of the basaltic tephra, and in part cold climate (Aradottir et al. 2000; Arnalds et al. 2002, 2013). This rate can be maintained for >100 years. Research shows significant increase in carbon with repeated measurements few years apart (Arnalds et al. 2013). One of the most notable change with restoration of the desert systems is a drop in pH from >7 to 5.5–6.5 in dryland systems. Clay formation takes longer time than the carbon accumulation (>50 to 100s of years to make significant changes). The organic matter increase results in improved water storage. However, the most dramatic changes occur on the surface, where vegetation that includes biological soil crust hinders surface movements by erosion and needle-ice (e.g., Oskarsson and Brynleifsdottir 2009). Infiltration in winter also improves gradually (Fig. 12.31; Orradottir et al. 2008; see also Strachan et al. 1998 for older restored soils). Temperature extremes and evaporation are reduced (Fig. 12.32).

Nitrogen accumulation is one of the most limiting factors after initial stabilization of the surface and the establishment of native species. As the deserts are almost devoid of nitrogen, the pool has to be accumulated from "scratch." Nitrogen deposition from the atmosphere in Iceland is only about 1 kg ha^{-1} $year^{-1}$. Studies that involve carbon accumulation for >50 years following restoration show that 20–40 kg N are accumulated each year in some lowland areas (which include 2 × 100–150 kg fertilizer applications), but much slower at higher elevations, from biological nitrogen fixation of soil crusts and other

Fig. 12.31 Measuring infiltration rates at the Geitasandur LandAid research cite. This an untreated control plot, with rapid infiltration in summer but very limited infiltration in winter time when the soil is frozen

organisms in areas that are not grazed. Fully vegetated systems have, however, >4,500 kg N in the top 30 cm on average (AUI unpublished data). International studies (see Whisenant 1999) show that a minimum of 750–1,000 kg N is needed to reach adequate levels for ecosystem functions. Thus, it takes decades or even >100 years at higher elevations to reach sufficient nitrogen levels for robust ecosystem functions.

Grazing slows the accumulation rates in the early successional stages substantially and can halt it altogether. Grazing has also very detrimental effect on biological soil crusts which are key "players" in stabilizing the surface and

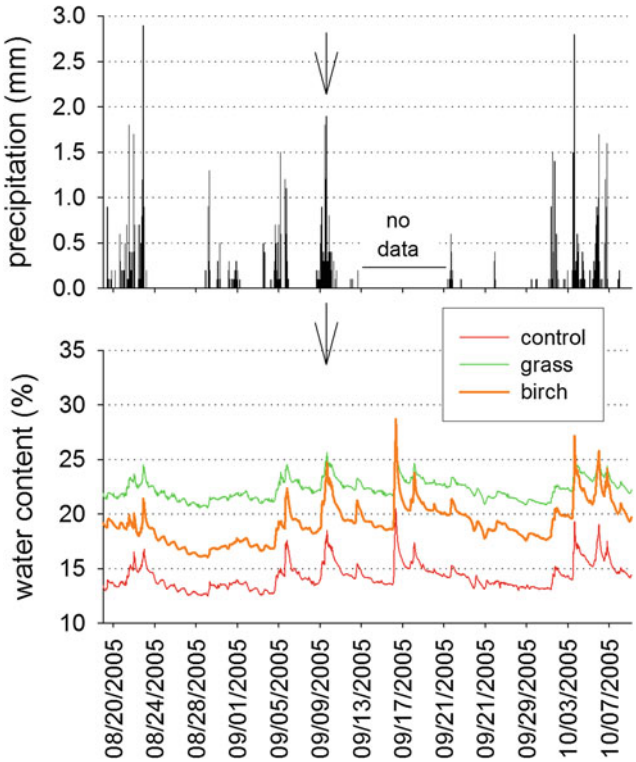

Fig. 12.32 Precipitation events and water contents at 5 cm depth in control (desert), and 5-year revegetated plots with grass/fertilizer and grass/fertilizer/birch treatments. The water content remains consistently lower in the control plots

accumulating the nitrogen. It is therefore important to prevent grazing in desert areas in Iceland in addition to multiple other factors that call for such intervention.

12.6.4 Many Ecosystems Are Being Reclaimed

Extensive areas have been revegetated in Iceland, and in many parts of the country, the vegetation cover is improving due to less or no grazing pressure on previously heavily grazed land. Much of the sandy deserts of the lowlands south and southwest of Mt. Hekla now have vegetation cover where barren sand was before. Many glacial rivers in South and Southeast Iceland have been channelized, reducing the extent of summer flooding and allowing for restoration and agricultural practices. Reclamation activities include seeding of grasses, applying fertilizers, and planting areas with trees (mostly by the Icelandic Forest Service but also by NGO's, farmers and other private landowners). Protecting from grazing is an important part of the land-healing activities, with 1,500 km^2 protected from grazing and additional 2,000 km^2 with partial protection and active land treatment in places by the Icelandic Soil Conservation Service (Halldorsson et al. 2011). The Icelandic Soil Conservation estimates that 571,000 ha (5,710 km^2) of land has been reclaimed in relation to the activities of the institute since 1907 (Crofts 2011). Halldorsson et al. (2011) listed all major restoration projects of the ISCS (in Icelandic).

Grazing practices have changed over the past decades. Horses are no longer grazed on the highland commons (with few exceptions), and the communal grazing period of sheep is becoming shorter. The number of sheep peaked around 1980 was nearly 1,000,000 winterfed ewes (see Arnalds and Barkarson 2003), but is currently below 500,000, which yet is much higher than the number during all the Middle Ages. Many sheep farms have been abandoned during the past decades, which have resulted in areas that now have limited grazing pressures in contrast to earlier days. Many of these areas are becoming greener with barren patches slowly becoming vegetated (e.g., around Reykjavík, in West Iceland, parts of the South, Southwest, West, and in the southwest part of the Westfjords). Reclamation and forestry activities are also slowly changing the Icelandic landscape toward more green, but almost exclusively in lowland areas. In some areas, more biological production is enhanced by a warm period, which can be related to global climate change (Hanna et al. 2004). The changes in green biomass show up in comparisons of satellite images 1982–2010 (Icelandic Institute of Natural History: http://www.ni.is/frettir/nr/13534).

The Icelandic Soil Conservation Service is involved in numerous land reclamation projects in co-operation with farmers and NGO's. The largest single project is the Hekluskógar project (Hekla Woodlands Project), which is intended to re-establish forests on the deserts around Mt. Hekla (Aradottir 2007; Oskarsson 2011). The project area is about 900 km^2 and a proportion of the area has very unstable ash and pumice surface. Much of the area was previously forested (birch and willows), but volcanic eruptions, wood harvesting, and continuous grazing (prevents regeneration of trees) have caused catastrophic erosion and desertification in the area. Woodlands are capable of receiving and stabilizing large amount of tephra, and the goal is to create resilient and stable ecosystems that can challenge inevitable future eruptions in the volcano. The method involves the use fertilizers and grasses to stabilize the surface and the establishment of islands of birch trees. The grasses give in, but provide safe sites for the birch to colonize from seed dispersal and subsequently spread further from clusters planted specifically for seed generation (Oskarsson 2011).

"Farmers Heal the Land" is a participatory approach project run by the Icelandic Soil Conservation Service, which involves about 15,000 ha (150 km^2) of land (see Arnalds 2005, 2011; Petursdottir 2011). The ISCS provides the fertilizer and guidance about land use and land reclamation. The areas involved are often used for grazing over

Fig. 12.33 The Þórsmörk area, a 4,000 ha restoration area, where birch, willows, and other natural vegetation have gained stronghold after protection from grazing, but the most severe erosion areas were fertilized and seeded for stabilization. The area in the foreground was barren soil until recently. Þórsmörk is now very popular for recreation activities. *Photo* © Gudjon Magnusson (Soil Conservation Service)

short periods, e.g., during the fall after full summer vegetation cycle. Large proportion of Icelandic farmers (about 650) are enrolled in the program (Petursdottir 2011).

Protection from grazing is often a major action taken to initiate and follow through land restoration by natural succession. Þórsmörk (The Garden of Thor) in the neighborhood of Eyjafjallajökull and the volcano Katla, a beautiful area popular for recreation activities, is perhaps one of the most impressive restoration areas in Iceland. It is about 4000 ha area where soil erosion and wood harvesting had nearly destroyed all the soils and the forest around 1900 (Oskarsson et al. 2011). During the twentieth century, the area was gradually protected from grazing and the birch forest has spread again over much of the area (Fig. 12.33). The Þórsmörk area is an example what can be achieved in restoration of Icelandic ecosystems.

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Regarding punctuation and Icelandic characters in citations: See note on punctuation in the Preface

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